Indian J. Phys. 64B (5), 329-345 (1990)

Lidar viewing of the atmosphere

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Received 30 November 1989, accepted 19 June 1990

Abstract : Light Detection and Ranging (LIDAR) systems have demonstrated capability of providing valuable quantitative information on structure and dynamics of the atmosphere. This article discusses fundamental Lidar equation and features of Raman Lidar, Differential Absorption Lidar (DIAL) and Doppler Lidar. Recent developments in lidar technology, leading to wide range of applications concerning meteorology, air pollution control and atmospheric research, are described. In meteorology, high resolution Lider measurement of vertical profiles of important meteorological parameters, are expected to provide important inputs to weather forcasting models. Lidar study of aerosol profiles and trace gas concentrations over the Indian region have shown a great potential in providing the quantitative information, not possible by other means. Future outlook in promoting lidar applications is presented.

Keywords : Lidar, Raman scattering, meteorology, aerosols, trace gases.

PACS Nos : 42.68.Rp, 92.60.- e

1. Introduction

First LIDAR (acronym for Light Detection and Ranging) was developed in 1962 (McClung et *al* 1962). In one of the first applications of laser beam, ruby laser was used as a range finder. Since then lidars have come a long way to play an increasing role as an active non-interfering remote sensing device in detecting atmospheric features (Zuev 1982). With the broad selection of lasers from ultra-violet to infrared now available, lidars have demonstrated unique capability to study the fine structure of atmosphere and its dynamics (Measures 1984). Today, continuous monitoring of important meteorological parameters upto mesospheric heights, determination of cloud base heights and their distribution, aerosol detection and trace gas analyses in the stratosphere down to troposphere, can be successfully performed using lidar Technology.

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Propagation of a laser beam in the atmosphere gives rise to scattering and absorption processes. The information contained in the back scattered signal has been analysed to determine atmospheric inhomogeneities. Principles of elastic and inelastic interaction as applied to atmospheric parameters have led to rapid developments in lidar technology. The observations through lidar offer greater flexibility of operation from ground stations as well as from aircrafts, ships and satellites. These possibilities have added considerably to our knowledge of atmospheric processes. Over the Indian region, the lidar measurements have provided spatial and temporal profile data, where in-situ measurements are rather scattered and scanty. In this review, LIDAR prospects in the study of certain important meteorological parameters and trace-gases like ozone, aerosol and other greenhouse gases for their impact on weather and climate are discussed in detail.

2. System features and principles

A lidar system essentially consists of a laser transmitter, a large aperture telescope and the detector. Receiver consists of a spectrum analyser, photo-detecting electronics, and a data acquisition processing unit. Selection of a particular laser source depends on the nature of constituent under study and the chosen parameter, which in turn determine the transmitted wavelength, duration of the pulse and the peak power requirement. A laser source having nano-second pulse generating capability with sufficiently high peak power, such as in Nd : YAG are proving suitable transmitters for most lidar applications. However, in some applications like the study of cloud base heights or other short range applications, continuous wave laser sources with much lower power outputs are sufficient.

A laser beam from the source is directed to the atmosphere with the help of transmitting optics. The beam in the atmosphere interacts with various inhomogeneities like gaseous molecules and aerosol particles, and is actively scattered in all directions. In a monostatic lidar, the portion of the incident energy that is scattered back towards the receiver is available for detection. The quantum of backscattering signal depends upon the number, size, shape and refractive index properties of gas molecules or particles interrupted by the incident energy, as well as the intensity and wavelength of incident signal. The output thus contains information on the concentration and range of atomic scatterers or absorbers at the target. It can be displayed on an oscilloscope or recorded on the data acquisition system. Signal to noise ratio determines the final resolution capabilities. Noise due to sunlight or background light can be minimised by use of narrow band filters. There can be noise, arising from detection optics, which is controlled through proper design of system parameters. A block diagram for a monostatic lidar in Raman configuration is shown in Figure 1.

In a bistatic geometry, the transmitter and the receiver are placed at a distance. A bistatic system is preferred, for determination of particle size distribution at different angles. Another advantage of using bistatic system is that continuous wave laser source can be used and it is not necessary to have extremly short duration pulse as needed for monostatic systems. However, with the development of nano- and pico-second pulse laser technology, bistatic arrangements are not much in use.

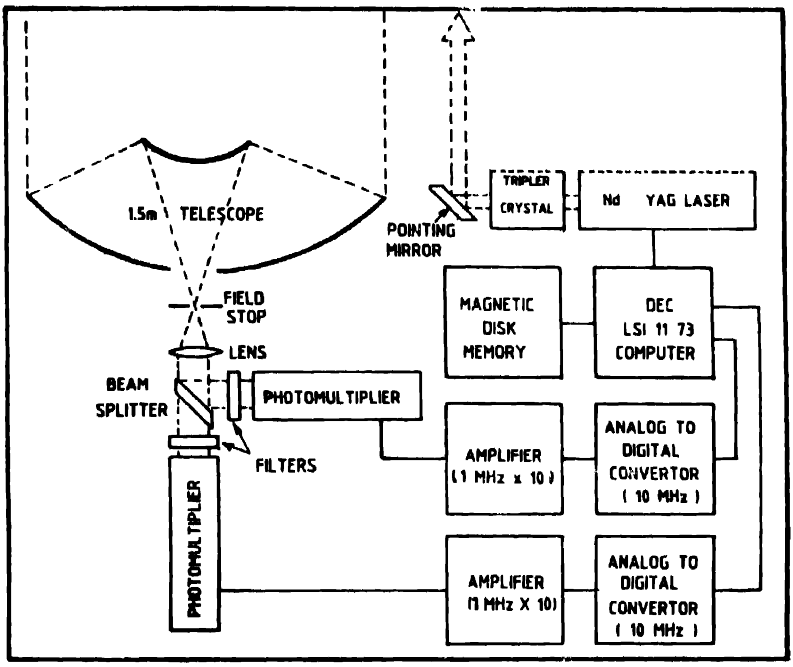

Figure 1.

A lidar equation giving backscattered power in terms of transmitted power (Collis and Russell 1976) can be written as,

$$P(R) = Po\frac{c\tau}{2}\beta(R)A_r R^{-2} \exp\left(-2\int^{R} \alpha(r)dr\right) \quad (1)$$

where,

Po is transmitted power,

c is velocity of light,

τ is pulse duration,

R is range,

A_r is effective receiver area,

$\beta(R)$ is volume scattering coefficient

$\alpha(r)$ is optical extinction coefficient of the atmosphere.

The backscattered signal is thus composed of elastic volume scattering coefficient as well as attenuation or extinction coefficient. Volume backscattering coefficient is again sum of scattering coefficients from gases and particulates, respectively.

(a) The contribution of Rayleigh backscattering coefficient due to the gaseous phase would be,

$$\beta_g = N_g \frac{d\sigma_R(\pi)}{d\Omega} \tag{2}$$

Here N_g is the number of gas molecules per unit volume and $\sigma_R(\pi)$ is Rayleigh backscattering cross-section. It is highly sensitive to the variations in the wavelength and varies inversely as its fourth power. The density of gas molecules can be determined knowing the Rayleigh backscattering coefficient.

(b) The volume backscattering coefficient of particulate matter or the aerosols, assuming them to be homogeneous spheres (Kerker 1969) can be described as,

$$\beta_p(\lambda) = \int^{\infty} \sigma_\beta(a, \lambda, m) N_p(a) da \tag{3}$$

σ_β is Mie backscattering cross section and is a function of particle dimensions a, measuring wavelength λ and the refractive index m. Here,

a is the radius of particulates,

λ is the wavelength at which measurement is carried out,

m is the complex refractive index of the particles, *

N_p (a) is the number of particles per unit volume with radius between a and $a+da$.

(c) In addition to these two factors, the attenuation takes place during the propagation of the laser beam in the atmosphere.

It could have scattering component as well as absorption component due to both gases and particles along the path. This attenuation coefficient can thus be written as,

$$\alpha = \alpha_{gs} + \alpha_{ps} + \alpha_{ga} + \alpha_{pa} \tag{4}$$

Here, α_{gs} and α_{ga} are scattering and absorption coefficient by gas molecules. α_{ps} and α_{pa} are scattering and absorption coefficient by aerosol particles.

Eqs. (1) to (4) generally describe the contribution of each atmospheric component to lidar signal. Actual lidar signal, however, is further modified by

*For more details on theory on propagation of optical waves in atmosphere, readers may refer to June and July, 1988 issues of *Applied Optices, Vol 27.*

inhomogeneous shape of particulates (Liou and Shotland 1971) and multiple scattering processes.

2.1. *Raman lidar :*

Both Rayleigh and Mie scattering are elastic collisions, hence the wavelength of the backscattered radiation does not undergo any change on scattering. In the case of an inelastic interaction, Raman scattering or flourescence can take place, giving rise to the shift in the wavelength of the received signal. According to Raman theory, the amount of shift in the wavelength of a coherently scattered radiation gives specific information on molecular constituents in the atmosphere. Different particles and gas molecules in atmosphere produce different spectral shifts. A shift can occur either due to rotational or vibrational transitions. Spectral shift towards longer wavelengths, gives rise to Stokes Raman Scattering. If it is towards shorter wavelengths, it is anti-Stokes Raman Scattering.

A lidar based on Raman Scattering or a 'Raman Lidar', in short, (Figure 1) identifies several molecules including nitrogen, water vapour etc and can also help in detection and location of unknown pollutants in the atmosphere. A Nd : YAG lidar system has been developed to measure the temperature by using Raman Scattering from nitrogen. Raman technique has given better resolution than differential absorption process as it does not have the limitation of smaller difference of gas concentrations as the light resolution becomes smaller. Raman lidars for study of atmospheric parameters have also become more accessible because of their cost-effectiveness in comparison to differential absorption systems. Another advantage with Raman Lidar has been that the laser wavelength of the transmitter need not be changed with different pollutants. However, achieving the adequate daytime signal to noise ratio with the Raman Scattering unless concentration of a pollutant is very high, will continue to be a challenge.

2.2. *Differential absorption lidar (DIAL) :*

Lidar based on differential absorption technique has emerged as an important tool in Atmospheric technology. The principle of Differential Absorption Lidar (DIAL) lies in simultaneous measurement of the extinction coefficients within and outside of absorption wavelengths of the gas being measured. DIAL uses a pair of laser beams of slightly different wavelengths, one of which is selected to resonate with the strong absorption band of the constituent under study. The atmospheric extinction and volume backscattering coefficients will be same at both these wavelengths. Hence the ratio of backscattering cross sections from the two wavelengths of the signals is a measure of absorption profile of the constituents. For computing the average value of a gas concentration (N) between say, ranges R_1 and R_2, ratio of two lidar equations (for on-absorption line and off-absorption) is determined (Browell 1983), and the value is expressed as,

$$N=\frac{1}{2(R_2-R_1)(\sigma_{\lambda 1}-\sigma_{\lambda 2})}\ln\frac{P_{\lambda 2}(R_2)P_{\lambda 1}(R_1)}{P_{\lambda 2}(R_1)P_{\lambda 1}(R_2)} \tag{5}$$

Here, $P_{\lambda 1}$ and $P_{\lambda 2}$ represent transmitted power at two wavelengths λ_1 and λ_2 for corresponding ranges R_1 and R_2. $(\sigma_{\lambda 1}-\sigma_{\lambda 2})$ is the difference between the absorption concentrations at the two wavelengths.

This makes it possible to determine presence and concentrations of minor pollutants, trace-gases or water vapour by appropriate selection of the resource wavelength matching with the absorption of constituent under study. This technique was first suggested by Schotland (1966), for determing water content profiles in the atmosphere. The major requirement for a differential absorption lidar is the availibility of tunable solid state laser sources in IR region with high spectral resolution and pulse energy greater than one Joule per pulse (Werner et *al* 1984). In addition, the laser source must be capable of producing, the following :

(i) a simultaneous emission at two wavelengths, with one in the absorption band of species being measured and

(ii) an optimisation of absorption wavelength, which is dependent on the altitude range under study.

Both path averaged and high vertical resolution profiles upto 50 km height are now possible to achieve. The powerful differential absorption method in combination with Raman scattering principles are finding promising future in measurements for a large number of molecular species over both land and ocean, during daytime as well as at night. Frequency doubled Nd : YAG laser pumped dye laser sources have tunability over a broad wavelength range, and are the most suitable candidate for DIAL operations, at present.

2.3. *Doppler lidar* :

The application of Doppler principle in the design of lidar involve measurement of frequency shift as a result of radial motion of the scattered target. A Doppler lidar is helpful in determining turbulent motion of air and of suspended particles in atmosphere. It is well known that the Doppler shift in frequency of backscattered signal is positive, when scatterer is moving towards the transmitter and negative, when it is moving away from it. One of the primary requirement in Doppler measurements is the high peak pulse energy of the order of 10 Joules, for achieving adequate return signal levels.

3. Lidar systems in meteorology

The principal role of lidars in atmospheric technology lies in accurate measurement of vertical and temporal profiles of important atmospheric parameters viz temperature, water vapor, wind and turbulence. Several important areas of meteorological applications such as initialisation of numerical weather forecast models, parameterisation of boundary layer and study of cloud physics are benefited from such high resolution measurements. In the regions which are not covered by in-situ meteorological sensors, lidars have demonstrated capability and offered a unique approach in remote sensing. In India, this technique is still in its infancy as far as meteorological applications are concerned. The description of global lidar systems and experimental results for some of the meteorological parameters are described below.

3.1. *Temperature measurements :*

Determination of atmospheric temperature using lidars make use of Rayleigh, Mie as well as Raman Scattering principles. In Rayleigh back-scattering, atmospheric molecules are the main scatterers of the laser pulse from a powerful Nd : YAG source. Information upto mesospheric heights with good accuracy and excellent vertical resolution for absolute measurement of temperature has been obtained. For lower tropospheric studies of less than 2 km, Raman scattering from atmospheric nitrogen or from air has been more fruitful. At further lower heights, Mie scattering by aerosols provide useful temperature profiles. Korb and Weng (1982) suggested the use of two wavelength lidar (DIAL) for making time-resolved temperature measurements from earth surface to tropospheric heights with an accuracy of 1 ' K and a vertical resolution of 2.5 km. The absorption coefficient of oxygen A-band relates to population in that level, which is turn in highly temperature sensitive.

Several indirect measurements in temperature are also reported. Chanin (1981) has computed temperature from density profiles in stratosphere and above using high power lasers. McGee and McIllrath (1979) proposed measurement of backscattered flourescence by OH radical from a space platform. Flourescence lidar techniques have been suggested to measure temperatures upto thermospheric heights (80 km-100 km). Inspite of considerable progress further improvements and developments are needed for use of lidars in routine monitoring of temperature on operational basis.

3.2. *Water vapour profiles :*

Knowledge of vertical profiles of water vapour in atmosphere is of prime importance in monsoon related studies and cloud physics. Water vapour profiles play important role in investigations of latent heat fluxes and air mass transportation over water bodies. Raman lidar can specially detect the Water vapour molecules and the profiles can be constructed at lower heights. Results of ground based laser Raman measurements using Q-Switched Ruby Laser, have shown good agreement with balloon Radiosonde measurements (Cooney 1971) in lower region of troposphere. The humidity profiles extending from 2 km to the tropopause have been obtained with a vertical resolution of 30 m using a third harmonic of Nd : YAG laser at 354.7 nm with the interference filter to isolate the vibrational Raman bands. Collis and Russel (1976) proposed DIAL technique using laser beam emitting in the range 725-732 nm, synonymous with water vapour absorption band for determining water vapour profiles in the troposphere with 0.5 km vertical resolution. Using DIAL eq. (5) water vapour profile from average amount of water vapour between any two ranges can be computed.

Simultaneous measurements of temperature and water vapour profile are possible (Mason 1975) by selecting two laser frequencies that coincide with centre of two temperature dependent water vapour transitions and the third frequency in non-absorbing region. Airborne DIALs are proving more functional for making range resolved measurements on regional scale. An air borne DIAL network has actually been proposed under world climate Global Energy and Water Cycle Experiment (GEWEX) for monitoring vertical profiles of water content in the mixed layer alongwith global cloud altitude observations.

3.3. *Wind and turbulence* :

The possibility of observing turbulence (Uthe and Russel 1972) and measuring wind velocity by actual tracking of inhomegeneities in the atmospheric particulate content was recognised in early stage using Doppler principles. To determine the air flow from inhomogeneities (Derr and Little 1970), a laser beam was split to propagate in two divergent paths and the time it takes for the inhomogeneities to move from one beam to other was measured. This time-of-flight technique measures the wind velocity component perpendicular to the sending beam. Combined with Doppler analysis for along the beam component, it has been recognised for determining three components of velocity for short range applications in an inhomogeneous field. Fiocco *et al* (1971) also succeeded in measurement of wind at short range from Doppler shift in backscattered signal.

For measurement of three dimensional wind profile over a large volume, laser beam is conically scanned around a vertical axis at different azimuths. The multiple azimuth data is analysed through computer analysis and detail study of wind structures has been made (Hardesty 1983). Using this technique, extensive wind measurements were carried out from ground and space borne lidar platforms. Carbon dioxide laser as well as Nd : YAG lasers have been found suitable for the Doppler shift measurements. Pulse energy requirement is estimated to be 10 Joules at peak power (Ottersten and Hagard, 1982).

In another system, variation in atmospheric refractivity is seen to result in laser scintillations. By observing drift of scintillation patterns, atmospheric turbulence studies can be carried out (Wang *et al* 1981). Global Doppler lidar networking is being proposed for direct measurements of winds through detection of line-ofsight Doppler shift in the back scattered signal by aerosols using CO_2 laser as a transmitter with input power at 10 J/pulse.

3.4. Atmospheric boundary layer parameters :

Depth of convective boundary layer has a determining effect on cloud formation and urban weather modification, in addition to playing an important role in monsoon dynamics studies (Goel and Srivastava 1989) and air pollution. As the top of atmospheric boundary layer is marked by a sharp discontinuity in the density profiles of troposheric aerosol and water vapour, a lidar is able to measure the aerosol densities and produce useful data in measurement of variable height of boundary layer, which varies from few hundred meters to few kilometers in height.

The choice of a particular system in boundary layer studies is determined by the application in view (Russell et *al* 1974). A ground based dual doppler lidar has been successfully used for these measurements with high accuracy (Kropfi et *al* 1982). Kolev et *al* (1988) have linked wind speed measurement in the region, to scattering of laser transmitted energy by aerosols present in the atmosphere. Lidar return signal is proportional to aerosol concentrations and is affected by aerosol inhomogeneity variations. Alternatively, lidar measurement of temperature profiles, in the absence of aerosol particles has also demonstrated ability of lidars for determining planetary boundary layer parameters (Kaimal et *al* 1982). Both ruby laser and Nd : YAG laser with 0.1 J peak energy at a pulse repetition rate of 10 Hz have been found suitable for this measurement with an accuracy of 50-100 meters vertical resolution. A new method for measurement of velocity spectrum width in the lower troposphere has been suggested (Ancellet et *al* 1989), using a pulsed CO_2 lidar with coherent detection, to study height of planetary boundary layer, interface of PBL/free atmosphere and large scale aerosol motion.

3.5. Ceilometry and cloud studies :

Lidar measurement of cloud base heights using low power laser is perhaps one of the most easily and early accomplished task (Collis 1969). Cloud ceilographs make use of ruby lasers as transmitters in the infrared range. A few laser ceilographs are in operation at certain airports in India.

For all cloud types and measurements a low power lidar does not suffice. It measures strong return from cloud droplets, but since the laser beam could not penetrate far, studies in cloud distribution are not possible. For this reason, lidar investigations of cloud formation and dynamics are meagre, although they are the major contributing factor in controlling solar radiation reaching Earth's surface. Distributive nature of variability characteristics in clouds present most difficult challenge in carrying out physical studies on them (Curran and Reading 1988).

Polarised lasers are proving valuable for getting insight into structure and composition of the clouds. A plane-polarised incident beam undergoes single scattering from say, spherical scatterers, would retain its polarisation on back-scattering. The depolarisation ratio defined as the ratio of unpolarised component and the component polarised as that of incident signal, would be zero. An observed value of depolarization ratio slightly more than zero, would indicate presence of either nonspherical particles or mutiple scattering processes. Assuming that there is no multiple scattering, different values of measured depolarisation ratio have been quantitatively assigned to various cloud factors (Pal and Creswell 1973). For example, a value of 0.3 would indicate presence of cirrus clouds. In practice corrections for multiple scattering, however, need be applied. Allen and Platt (1977) were able to detect the multiple scattering components of clouds using special technique of centre blocked field stops to restrict the receiver field of view. Hall *et al* (1988) have proposed pulse Doppler lidar to determine infrared extinction coefficient in cirrus clouds.

It is possible to infer freezing level in clouds, indentify ice water precipitation mixing ratio and determine number of other parameters such as opacity, cloud thickness, and reflectivity from these measurements. Smiley and Morley (1981) tested the applicability of lidar depolarisation ratio techniques to polar regions for discriminating ice and water particles in the Antarctic atmosphere. Significant cloud observations of dense tropospheric clouds heavier in water content to high altitude cirrus clouds, could also result from lidar observations.

4. Aerosols and minor constituent detection in climate research

Monitoring of aerosols and minor constituents in the troposphere and stratosphere have an increasing role of play in understanding of many atmospheric processes. Related to there are phenomena such as radiation budget of atmosphere, green house effect and ozone depletion, which are prominent climate issues being faced by global scientific community. These changes are being caused by natural and man-made sources. Lasers have added to our capabilities in identifying the causes by providing more information on spatial and temporal profiles and are steadily replacing in-situ measurements. In recent years, several observational strategies have been developed in the country, which may have a role to play in establishing a firm knowledge of potential impact of natural as well as man-made pollutants on climate change. In this section, a brief overview of laser devices for these prospective applications is described.

4.1. Aerosol measurements :

Aerosol defined as "suspended particles" affect the radiation budget through scattering and absorption processes and also determine the cloud condensation properties. It has been stipulated that an abrupt increase in aerosol scattering signal above the cloud top can determine the depth of mixing layer (Browell *et al* 1980). The mathematical modelling to quantify aerosol effects on climate change has been attempted (Dave 1973 ; Schneider and Dickinson 1974) but testing of most models is hampered by lack of suitable data.

Lidar techniques have proven to be a powerful method among others for studying the aerosol profiles in the atmosphere. Lidars in pulsed or continuous wave mode are capable of providing range resolved information on aerosol characteristics. Over Indian regime, Krishnamurthy (1988) have measured aerosol concentrations and size distributions in the lower troposphere. In a CW lidar experiment at Trivandrum (Parameswaram and Krishnamurthy 1986) argon ion laser operating at 514.5 nm was used as a transmitter in a bistatic arrangement for studying angular dependence of aerosol scattering. These measurements extended upto an altitude of 2 km, have indicated presence of turbulence layers leading to accretion of aerosols between these layers. It has been stipulated that aerosols can act as tracers of stratified turbulence in lower atmosphere.

A pulsed ruby lidar at 695.4 nm has been in operation at Trivandrum since October 1986, to study the characteristics of extinction profiles of aerosols upto high altitude ranges. The extinction profile showed a prominent maximum in the altitude range of 3-4 km with a seasonal variation. The sharp maximum observed in summer as distinguished from the stratospheric aerosol extinction seasonal variation at an altitude of 21.3 km. The mean profiles of aerosol extinction/number density in a tropical coastal region is shown in Figure 2. Nair *et al* (1988) inferred from seasonal variations in wavelength dependence of aerosol optical depths a monomodal structure of columnar aerosol size distribution in summer and monsoon and a bimodal structure in winter months. Altitude dependence of aerosol size distribution was also studied during a co-ordinated experiment on Indian Middle Atmosphere Programme. A CW argon ion lidar with output power of 4W has been used for studying seasonal variation in vertical distribution of aerosols in the lower troposphere over Poona region (Devara and Raj 1989).

In stratosphere, and aerosol layer of few kilometer thickness is known to centre near 20 km altitude as a quasi-permanent feature. Concentration of gases in this layer is found to increase on volcanic erruptions or by meteoric phenomena. Lidar data could provide valuable information on continuous and consistent basis in relation to such extingencies (Mc Cromick and Fuller 1975). A beam of higher peak pulse energy is required for tropospheric aerosol measurements. The lidar technique involve measurements of vertical profile of received signal resulting from elastic backscattering by stratospheric gases and aerosoles under disturbed conditions and comparing it with signal profile that would result for gas phase of stratosphere alone. At an altitude z scattering ratio (McCormick et al 1984) is given by

$$\xi(z)=1+\frac{\beta_p(z)}{\beta_g(z)} \tag{6}$$

$\beta_p(z)$ and $\beta_g(z)$ are elastic particulate and gaseous volume scattering coefficients at altitude z. Suitable remote sensing systems have been developed using laser sources and a few lidar systems are presently in operation in Northern Latitudes for measuring global stratospheric aerosol profiles (WCRP Report 1988).

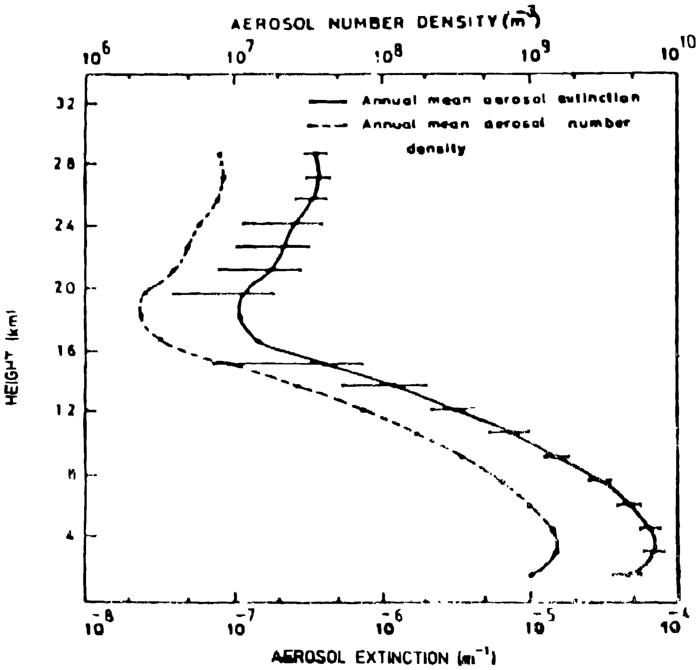

Figure 2.

At further heights in the atmosphere, extending from 30 to 90 km, aerosol content becomes very low. As the atmospheric molecules are the main scatterers in this region, lidar backscattering signal essentially corresponds to Rayleigh Scattering. In this region interesting seasonal and diurnal variations have been observed (Kent and Keenliside 1974) using lidars and DIAL systems. Russel and Grams (1975) model on dimate effects of aerosol predicts that an aerosol layer of thickness more than a critical value will cause a decrease in system albedo and vice versa. Harshvardhan and Cess (1976) further computed a decrease in surface temperature change due to stratospheric aerosol layer and concluded that an increase in corresponding solar albedo will thus dominate over the increase in greenhouse effect due to stratospheric aerosol layer.

4.2. Ozone profiles :

Ozone envelops the earth at a height of 25-40 km and protects the biosphere from harmful effects of ultraviolet radiation. Direct and indirect methods of measuring ozone fluctuations due to perturbations caused by human activity in the atmosphere have been developed (Vivekananda and Arora 1988). The chemical effects of trace gases such as CFC's, carbon monoxide, nitrous oxide and others are strongly coupled and are linked with observed ozone depletion.

Monitoring of atmospheric ozone has been carried out since 1970 using Dobson spectrometer and balloon borne ozone-sonde measurements. First remote measurement of ozone profiles using lidar was obtained in 1980. Using CO_2 laser or Nd : YAG pumped tunable dye laser systems with transmitting wavelength within absorption band of ozone i.e. 280-310 nm ozone concentration have been determined. These lidar measurements were found comparable with in-situ ozone sonde measurements made in the boundary layer (Browell 1983). Laser induced flourescence method operating in DIAL mode was proposed by Megie *et al* (1985) for determining ozone absolute concentrations. Ozone lidar can also be used to study ozone response to variations in ambient temperature and Solar ultraviolet emission at a single location, for extended time periods.

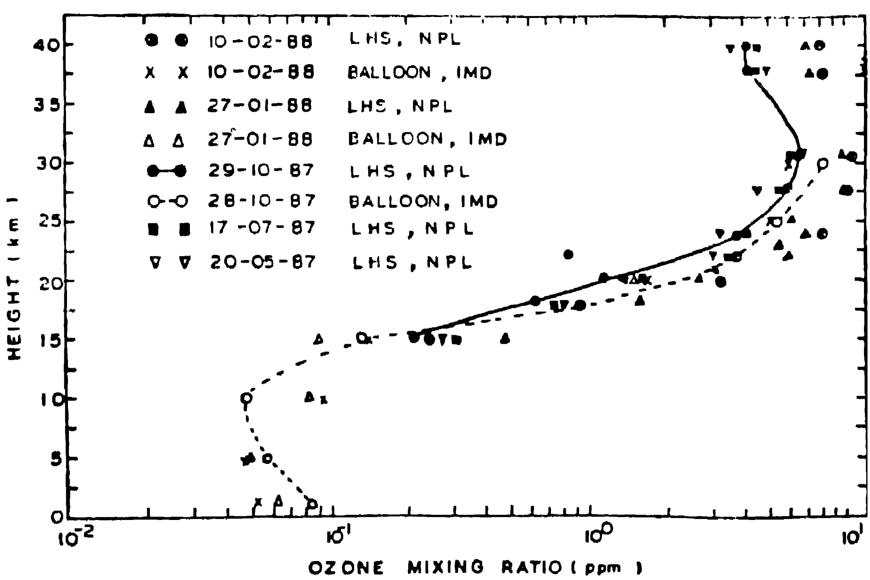

Figure 3.

To study the minor constituents in atmosphere the use of IR and CO_2 Laser was proposed by Dr A K Saha at National Physical Laboratory (Jain *et al* 1986). A laser heterodyne system consisting of tunable CO_2 laser has been developed (Jain 1989) for detection and study of trace gas profiles over Delhi. With its *ultra high spectral resolution in the IR region, ozone profiles have been obtained in the height range of 15-40 km with a resolution of 2-3 km as shown in Figure 3. The laser heterodyne system relies on the matching of discrete CO_2 laser transitions with the constituent absorption line. A more versatile system with microprocessor control data analysis and tunable solid state semiconducting diode lasers as sources is under development.*

4.3. *Other pollutant gases :*

Studies of other trace-gases from environmental health stand point and as major cause of concern in climate change are becoming increasingly important. A large number of these trace-gases and industrial pollutants thus need to be monitored for their identification and measurement of their concentration profiles. Since many of these trace-gases have absorption bands overlapping with tunable CO_2 laser lines, lasers are proving to be most powerful techniques for their investigations (Johnson 1969). DIALs were successfully utilized for measurement of NO_2 (Rothe *et al* 1974) and SO_2 emissions upto an height of 2 kms (Browell 1982). Grant and Hake (1975) proposed the DIAL wavelength pair of 292-293 nm for measurements of SO_2 as well as O_3 in atmosphere. Nd : YAG laser pumped dye laser, with frequency doublers was found suitable. Spectral studies of HCl and methane have been reported by Fredrickson *et al* (1979). Inversion techniques have been developed to retrieve height profile of ozone, NO_2 and water vapour in stratosphere using heterodyne system at NPL.

Lidars have also made profound impact in the study of specific gaseous contamination as they disperse from pollution sources. Cassidy and Reid (1982) have proposed use of mobile lidar systems for measuring the flow of NO_2, NO emissions in the Industrial area. The monitoring of CO and CO_2 in atmosphere is also possible using infrared laser beam at 2.3 μ (Henningson *et al* 1974), although not many studies are conducted. An integrated approach using lidars in remote sensing of environmental pollutants has been emerging recently.

6. Summary and outlook

A number of useful LIDAR techniques have been demonstrated for applications in atmospheric technology. It is not possible to cover all the studies and extensive research work done in this area in a short over view. Undoubtedly, lidar capabilities for gathering new data simultaneously has been well established. Such studies will be of immense value for numerical modelling and monsoon forecasting programmes. Recent developments in Raman lidar technology and DIAL based systems, have demonstrated unique potential for collection of temporal and spatially resolved data for trace-gases and pollutants with greater accuracy. Many research avenues where lidar can make unique contributions are now opening up.

For global atmospheric observation, the expansion of major lidar networks through ground and air borne platforms is underway. Recent attempts have been made for mounting space based lidar probes in the next generation of Earth Observation Satellites. NASA's Lidar-in-space Technology Experiment (LITE) expected for early 1990s, is a feasibility experiment for future lidar payloads in space plaftorms for Atmospheric research. A network of satellite based lidar observations is proposed for this decade (Poole et *al* 1988).

Over Indian continent, several important contributions have been made to studies particularly related to aerosol profiles due to man-made causes and measurements of ozone, nitrous oxide and water vapour profiles in some regions. Argon ion and ruby laser lidars are in operation at Trivandrum and Indian Institute of Tropical Meteorology and a laser heterodyne system at NPL, New Delhi. In the study of meteorological parameters, better resolved data for longer durations and continuous spatial profiling, in place of scattered data from point sensors such as towers, radiosonde balloons are required. Co-ordinated experiments addressed to study of atmospheric transmissivity, boundary layer studies, cloud physics, and minor constituents would help in solving some of the issues of real data needs in programmes aimed at study of climate changes and weather forecasting. In the years to come, lidars would be instrumental in the study of formation of low level temperature inversions over urban areas leading to conditions likely to be responsible for severe pollution events and in predicting their impact on climate changes. Department of Science and Technology has a programme to promote lidar studies of meteorological parameters during the VIII plan.

With some of these ultimate goals, it should be kept in view that present lidar technology faces certain limitations in the use of visual and near infrared laser sources, because of lack of suitable detectors. Moreover, lidars operating in visible range suffer from high daytime background noise. A lidar operation is restricted to the region of adequate optical transmission, a parameter which is dependent on the source wavelength. Lidars for ultraviolet range are harmful to the eyes if operated from ground platforms. With these limitations, further advancement in lidar applications put specific demands for synthesis of special lasers. Indegenous efforts in constructing lasers suitable for such applications have been taken up by groups at IRDL Dehradun, BARC, IIT Kanpur, University of Poona and VSSC Trivandrum. However, to keep pace with the fast developments in semiconductor laser technology, more efforts are needed. Development of compact light weight solid-state laser arrays, capable of emitting high power are likely to revolutionise the lidar systems in near future.

Acknowledgments

The authors express sincere gratitude to Dr Vasant Gowariker, Secretary, Department of Science and Technology (DST) for the encouragement.

References

Allen R J and Plalt C M 1977 *Appl. Optics* **16** 193

Ancellet G M, Menzies R T and Grant W B 1989 *J. Atm. Ocean Tech.* **6** 50

Browell E V 1982 *Opt. Engg.* **21** 128

1983 *Optical and Laser Sensing* eds D K Killinger and A Mooradian (Berlin : Springer-Verlag) p 138

Browell E V, Carter A F and Shipley S T 1980 *Proc. of the IAMAP Int. Quadrennial Ozone Symp. NCAR, Boulder, Co,* USA, Aug 4-9

Cassidy D T and Reid 1982 *Appl. Optics* **21** 1185

Chanin M L 1981 *Paper presented at Symposium on Application of Lidar to Atmospheric Radiation and climate, Third special Assembly, IAMAP, Hamburg,* FRG, 17-28 Aug

Collis R T H 1969 *Lidar : In advances in Geophysics* 13 eds H E Landsberg and J Van Mieghem, (New York : Academic) p 113

Collis R T H and Russel P P 1976 *Topics in Applied Physics* ed E D Hinkley Vol 14 (Berlin: Springer-Verlag) p 71

Cooney J A 1971 *J. Appl. Meteorol.* **10** 301

Curran R J and Reading C 1988 *WCRP-5, WMO/TD-No. 215*

Dave J V 1973 *J. Appl. Meteorol.* **12** 601

Derr V E and Little C G 1970 *Appl. Optics* **9** 1976

Devare P C S and Raj P E 1989 *IETE Tech. Rev.* **4** 412

Fiocco G, Benedotti-Michelangoli G, Maischborger K and Madouna E 1971 *Nature* **229** 78

Fredrickson K, Galle B, Nystrom K and Svanberg S 1979 *Appl. Optics* **18** 2998

Goel Malti and Srivastava H N 1989 *Vayumandal* **19** 1

Grant W B and Hake R D (Jr) 1975 *J. Appl. Phys.* **46** 3019

Hall F F, Cupp R F and Troxel S W 1988 *Appl. Optics*

Hardesty R M 1983 *Optical and Laser Remote Sensing* eds D K Killinger and A Mooradian (Berlin: Springer-Verlag) p 350

Harshvardhan and Cess R D 1976 *Tellus (Sweden)* **28** 1

Henningson T, Carbuny M and Byer R L 1974 *Appl. Phys. Lett.* **24** 242

Jain S L 1989 *Indian J. Radio Space Phys.* **18** 175

Jain S L, Arya B C, Nakra D R and Saha A K 1986 *Indian J. Radio Space Phys.* **15** 29

Johnson W B 1969 *J. Appl. Meteorol.* **8** 443

Kaimal J D, Abshire N L, Chadwick R S, Deckor M T, Hooko W H, Kropti R A, Pasqualuci W D N F and Hildebrant P H 1982 *J. Appl. Meteorol* **21** 1123

Kent G S and Keenliside W J 1974 *J. Atmos Sci.* **31** 1409

Kerker M 1969 *The Scattering of Light and other Electromagnetic Radiation* (New York : Academic) p 92

Kolev I, Parvanov D and Kaprielov B 1988 *Appl. Optics* **27** 2524

Korb C L and Weng C Y 1982 *J. Appl. Meteorol.* **21** 1346

Krishnamurthy B V 1988 *Indian J. Radio Space Phys.* **17** 203

Kropfi R A, Pasqualucci W D N F and Hildebrant P H 1982 *J. Appl. Meteorol.* **21.** 1123

Liou K N and Shotland R M 1971 *J. Atm. Sci.* **28** 772

Mason B J 1975 *Appl. Optics* **14** 76

McClung F J, Hardy K R and Glover K M 1962 *J. Appl. Phys.* **33** 828

McCormick M P and Fuller W H (Jr) 1975 *Appl. Optics* **14** 4

McCormick M P, Swissler T T, Fuller W H, Kent W H and Osborn M T 1984 *Geof. Int.* **23** 187

McGee T J and McIlrath T J 1979 *Appl. Optics* **12** 2036

Measures R M 1984 *Laser Remote Sensing* (New York : John Willey) p 325

Megie G, Ancellet G and Pelon J 1985 *Appl. Optics* **24** 3454

Nair P R, Krishnamurthy K and Krishnamurthy B V 1988 *Second Workshop on IMAP Scientific results, VSSC, Trivandrum*, India

Ottersten H and Hagard A 1982 *Air Sea Interaction* ed F Dobson, L Hassc and K Lavis (New York : Plenum) p 543

Pal S R and Creswell A I 1973 *Appl. Optics* **12** 1530

Paramswaram K and Krishnamurthy B V 1986 *Indian J. Radio Space Phys* 145

Poole H E, Cox J W, Couch R H and Fuller W H (Jr) 1988 *A Lidar Technology Experiment from Space Shuttle* (Private Communication)

Rothe K W, Brinkman U and Walther H 1974 *Appl Phys.* **4** 101

Russel P B and Grams G W 1975 *J. Appl. Meteorol.* (USA) 1037

Russel P B, Uthe E E, Ludwig F L and Show N A 1974 *J. Geophys. Res.* **79** 5555

Schotland R M 1966 *Proc. 4th Sym. on Remote Sensing of the Environment*, University of Michigan. Ann Arobr, USA p 273

Schneider S H and Dickinson R E 1974 *Rev. Geophys. Space Phys.* **12** 447

Smiley V N and Morley B M 1981 *Appl. Optics* **20** 2189

Uthe E F and Russell P B 1972 *Bull. Am. Met. Soc.* **53** 358

Vivekanand M and Arora R S 1988 *Curr. Sci.* **57** 1103

Wang T, Ochs G R and Lawrence R S 1981 *Appl Optics* **20** 4073

WCRP Report 9 1988 WMO/TD-No. 233 p 17

Werner J, Rothe K W, Walther H 1984 *Proc. Quardrennial Uzone Symposium* Halkidiki, Greece, (Dordrecht : D Reidel) p 842

Zuev V E 1982 *Laser beams in the Atmosphere, Translated from Russian by* J S Wood (New York : Consultants Bureau)

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